Ocean Currents Evident in Satellite Wind Data

Kathryn A. Kelly,[1] Suzanne Dickinson,[1] Michael J. McPhaden,[2] and Gregory C. Johnson[2]

Abstract. Satellite-mounted radar scatterometers designed to quantify surface winds over the ocean actually measure the relative motion between the air and the ocean surface. Estimates of the wind stress from conventional surface wind measurements are usually derived neglecting ocean currents. However, when the relative motion is used, the differences in the estimated stress can be as large as 50% near the equator and may even reverse sign during an El Niño. This assertion is supported by the strong relationship between the surface currents measured by the Tropical Atmosphere-Ocean (TAO) array in the Pacific Ocean and the differences between the winds estimated from scatterometer data and those measured by TAO anemometers. The fact that the scatterometer measures relative motion, and not wind alone, makes scatterometer-derived stress a more accurate representation of the boundary condition needed for both atmospheric and oceanic models than stress fields derived neglecting ocean currents.

Introduction

Accurate measurements of surface stress are needed to understand air–sea coupling and to improve predictions of the El Niño/Southern Oscillation (ENSO) and decadal climate variability [*Huang and Schneider*, 1995; *Kessler et al.*, 1995; *Liu et al.*, 1996]. After the very large El Niño in 1982–83, a moored array of instruments, called the Tropical Atmosphere-Ocean (TAO) array, was installed in the equatorial Pacific Ocean to facilitate detection and prediction of ENSO. This array spans the width of the Pacific Ocean between 8°N and 8°S. It consists of approximately 70 buoys, equipped with instruments to measure meteorological and oceanographic data including surface winds, and in a few locations, ocean currents [*McPhaden*, 1995]. The TAO array has led to fundamental progress in understanding and modeling the physical processes of ENSO [*McPhaden et al.*, 1998].

Ocean winds are measured globally using satellite-mounted radar scatterometers, providing nearly daily coverage. The NASA scatterometer (NSCAT) on the Japanese satellite ADEOS-I greatly expanded coverage compared to the European Space Agency's ERS scatterometers, which began measurements in 1991. NSCAT successfully measured global ocean winds during the onset of the 1997–98 El Niño, from its launch in August 1996 until a spacecraft power failure terminated the measurements in June 1997 [*Naderi et al.,* 1991]. NASA launched a replacement sensor, SeaWinds on QuikSCAT, which has been taking data since mid-July 1999. Both the NSCAT and QuikSCAT scatterometers measure winds in roughly 25 km^2 patches, with NSCAT covering most of the ocean in two days and QuikSCAT covering most of the ocean in one day.

[1]Applied Physics Laboratory, University of Washington, Seattle
[2]Pacific Marine Environmental Laboratory, NOAA, Seattle

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Scatterometer Measurements

Scatterometers measure microwave radar backscatter from centimeter-length waves on the ocean surface. The amount of backscatter is determined primarily by the speed of the wind, but modulation of the backscatter with the direction of the wind allows an estimate of vector wind. An empirical retrieval algorithm is used to convert backscatter measurements into candidate wind vectors [*Wentz and Smith*, 1999] and a second algorithm is used to select the best vector [*Huddleston et al.*, 1999]. The retrieval algorithm is derived from wind observations that have been adjusted to be the equivalent neutral-stability wind at 10 m; the buoy winds used here have had the same adjustment [*Liu et al.*, 1979].

Numerous experiments have demonstrated the effects of sea state and motion due to waves on radar backscatter [*Colton et al.*, 1995; *Plant et al.*, 1999], but less attention has been given to the effects of larger-scale ocean currents. Because centimeter-scale waves are generated by air moving over the ocean, the scatterometer measures winds relative to the moving ocean surface, not the wind relative to a stationary point. Thus, the wind speed inferred from scatterometer data (Fig. 1) should be lower than the wind speed measured by anemometers when the current is in the same direction as the wind. Conversely, scatterometer wind speed should be higher when the current opposes the wind. The relative motion measured by the scatterometer is the quantity needed to estimate air-sea fluxes, in particular, the momentum flux, or wind stress. Over most of the ocean, wind speeds are of order ten times larger than current speeds, so this effect is not usually large. Over an energetic Gulf Stream ring in the North Atlantic, however, the NSCAT winds exhibited a modulation large enough to estimate the azimuthal component of the ring current [*Cornillon and Park*, 2001]. The tropical Pacific Ocean, with its relatively gentle trade winds of 5–9 m s^{-1} and strong currents, sometimes exceeding 1 m s^{-1}, is a region where currents are expected to make large-scale contributions to stress estimates.

TAO/Scatterometer Comparisons

To check for possible biases in the empirical calibration of the scatterometer, we compared thousands of wind vectors measured by the TAO array in the equatorial Pacific Ocean with the vectors estimated from data gathered by NSCAT and QuikSCAT. Here we show that ocean currents make a large contribution to the mean differences between the scatterometer and buoy winds.

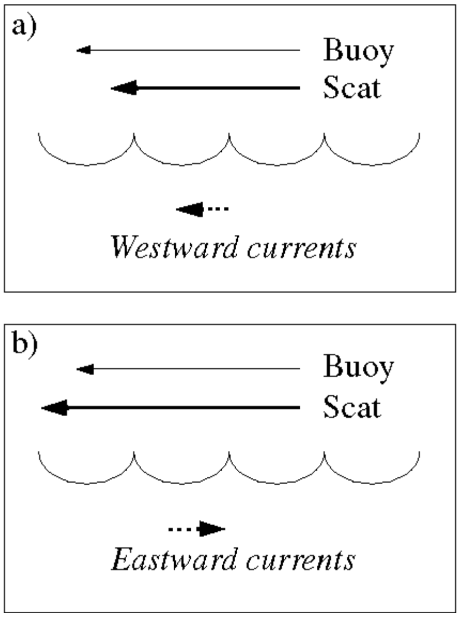

Figure 1. Schematic of the buoy wind vectors, scatterometer vectors, and ocean currents (a) for currents aligned with the winds and (b) for currents opposing the winds.

First we compared the ocean currents measured by the TAO array with the difference between the winds measured by the TAO anemometers and those measured by NSCAT. In this comparison, the NSCAT vectors were first screened for contamination by precipitation [*Dickinson et al.*, 2000] and then for differences in direction of more than 60° from TAO winds. (The scatterometer winds occasionally include vectors that are in error by approximately 180°[*Caruso et al.*, 1999], owing to the similarity of backscatter values in the upwind and downwind directions.) These two screenings eliminated approximately 10% of the scatterometer vectors. In addition, a mean directional bias of approximately 10° was removed. Finally, a running average over five days was applied to the NSCAT winds, which have irregular temporal sampling.

The results of the NSCAT comparison are shown as a time series on the equator at 140°W that covered the onset of the 1997–98 El Niño. During this period, the daily averaged anemometer winds adjusted to 10-m height were always easterly (Fig. 2a). Before the outbreak of El Niño, the currents at 10 m depth were aligned with the wind (both westward) (Figs. 1a and 2c) and the TAO winds exceeded the NSCAT winds by approximately 1 m s^{-1}. Beginning in December 1996, episodes of westerly winds in the western equatorial Pacific sent oceanic Kelvin waves across the Pacific and currents along the equator reversed to eastward (Figs. 1b and 2c) [*McPhaden and Yu*, 1999]. During the latter period, the NSCAT winds exceeded the TAO winds by approximately 1 m s^{-1}, the expected effect of the scatterometer measuring relative motion. Comparison of the currents (Fig. 2c) and the difference between the TAO and NSCAT winds (Fig. 2b) shows they are quite similar in magnitude and direction. The correlation between the zonal components is 0.61 (95% significance level is 0.48).

The TAO array presently samples currents at only a few meridians on the equator, which severely limits the region of comparison. However, acoustic Doppler current profilers (ADCPs) mounted on the support vessels maintaining the TAO array provide twice-yearly vertical sections (from 8°S to 8°N and from 25 m to nearly 400 m) of currents along eight TAO meridians from 165°E to 95°W [*Johnson et al.*, 2000]. These current measurements were compared with the difference between the TAO and QuikSCAT wind vectors. For this comparison objective mapping of the zonal velocity effectively extrapolates values to 5-m depth from measurements of vertical shear below 20 m. The 5-m zonal velocities were not significantly different (rms of 0.11 m s^{-1}) from those measured at 25-m depth.

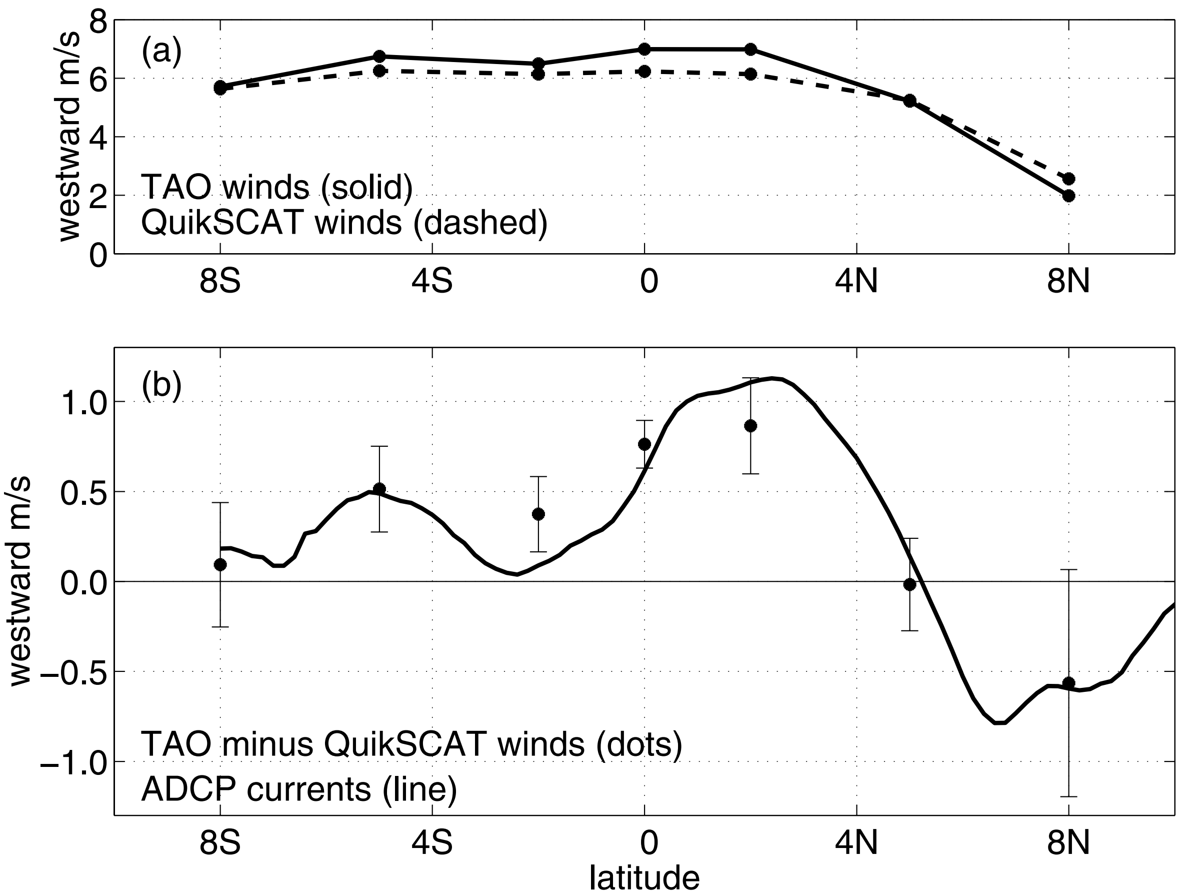

Figure 3. Zonal winds and currents averaged over three meridians (155°W, 140°W, 125°W). (a) Zonal winds from TAO (solid line) and from QuikSCAT (dash line), westward is up. (b) ADCP zonal currents extrapolated to 5-m depth (solid line) between 16 September and 31 October 1999. Average difference between TAO and QuikSCAT zonal wind components at TAO buoys (dots) with 95% confidence intervals.

The early part of the QuikSCAT mission was during the 1998–99 La Niña, so mean winds (at the locations and times of available ADCP data) were consistently easterly for both TAO (Fig. 3a, solid line) and QuikSCAT (dash line). Zonal currents in the tropical Pacific Ocean had little temporal variation, but significant meridional structure. The average zonal surface current (Fig. 3b, line) calculated from three ADCP sections taken during boreal Fall 1999 along 155°, 140°, and 125°W reveals maximum westward speeds of 1.1 m s^{-1} in the South Equatorial Current (SEC) at 2°N and maximum eastward speeds of 0.6 m s^{-1} in the North Equatorial Countercurrent (NECC) at 7°N. This current structure is strikingly similar to the difference of the TAO and the QuikSCAT zonal winds during the time period of the sections (Fig. 3b, dots). Scatterometer winds are less than TAO winds in the SEC (2°N) and greater than TAO winds in the NECC (8°N), with the difference being nearly equal to the zonal currents. Note that a small speed adjustment (0.2 m s^{-1}) has been made to the QuikSCAT winds, which is just equal to the mean wind speed difference (TAO minus QuikSCAT) after accounting for the currents; this adjustment is smaller than the stated accuracies of either the TAO or the QuikSCAT winds. The high level of agreement in Fig. 3b suggests that the differences between anemometer and scatterometer zonal winds in this region are primarily due to ocean currents.

There was a directional bias of approximately 11° (QuikSCAT to the right of TAO), similar to that seen in our NSCAT comparison and in a comparison of NSCAT data with buoys from both TAO and the National Buoy Data Center (NDBC) [*Wentz and Smith*, 1999]. A recent examination of the calibration of the TAO anemometers revealed a mean bias of 6.7° counterclockwise of the true direction, which would account for much of the discrepancy [*Freitag et al.*, 2001]. This error in direction was discovered during the writing of this article and so no corrections have been made to the TAO winds. The direction bias has been corrected in all TAO moorings deployed after November 2000.

Discussion and Conclusions

The fact that the scatterometer measures the relative motion between the atmosphere and the ocean has important implications for understanding and modeling air–sea coupling, particularly for ENSO prediction. Modeling this coupling requires a knowledge of the stress exerted by the atmosphere on the ocean, which in turn requires the relative motion. To quantify the impact of including ocean currents in wind stress estimates, we modified a commonly used stress product [*Stricherz et al.*, 1992] by the value of the currents estimated from the ADCP data. This modification reduced the median stress 20% (with a peak reduction of

50%) around 2°N, at the core of the westward SEC, and increased the median stress 10% (with a peak increase of 30%) around 7°N, at the core of the eastward NECC. These differences are large enough to affect ocean circulation models. Previous estimates of the effect of including ocean currents in wind stress estimates suggested a difference of 10–20% [*Halpern*, 1988]. The modification in the curl of the wind stress, essentially the difference between the wind stress at the two latitudes, would be even larger than the stress modification.

In a previous analysis, the stress fields from NSCAT were compared with wind stress derived from the European Centre for Medium-range Weather Forecasts (ECMWF) [*Kelly et al.*, 1999]. The NSCAT stress was substantially different from the ECMWF stress, particularly near the Intertropical Convergence Zone (ITCZ). Some of the differences could be due to the difficulty of modeling the strong convergence [*Trenberth et al.*, 1990] or to precipitation contamination in the NSCAT data, as suggested by *Yu and Moore* [2000]. However, the curl of the NSCAT wind stress was systematically more positive at about 7°N than the ECMWF curl, consistent with our estimates of the effects of ocean currents on the stress. In addition, our analyses here were done with scatterometer data which was screened to eliminate precipitation effects. Therefore, our comparisons suggest that neglect of ocean currents is the dominant factor contributing to the ECMWF/NSCAT differences near the ITCZ.

Scatterometer wind stress estimates have the potential to greatly improve our understanding of climatically vital air–sea fluxes, including momentum, heat, and gases. In addition, the large differences between stress estimates based on scatterometer data and stress estimates based on wind data alone highlight the importance of including currents in coupled atmosphere–ocean models, especially in the tropical Pacific.

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K. A. Kelly and S. Dickinson, Applied Physics Laboratory, University of Washington, Box 355640, Seattle, WA 98195-5640. (e-mail: kkelly@apl.washington.edu)

M. J. McPhaden and G. C. Johnson, Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE, Bldg. 3, Seattle, WA 98115-6349.

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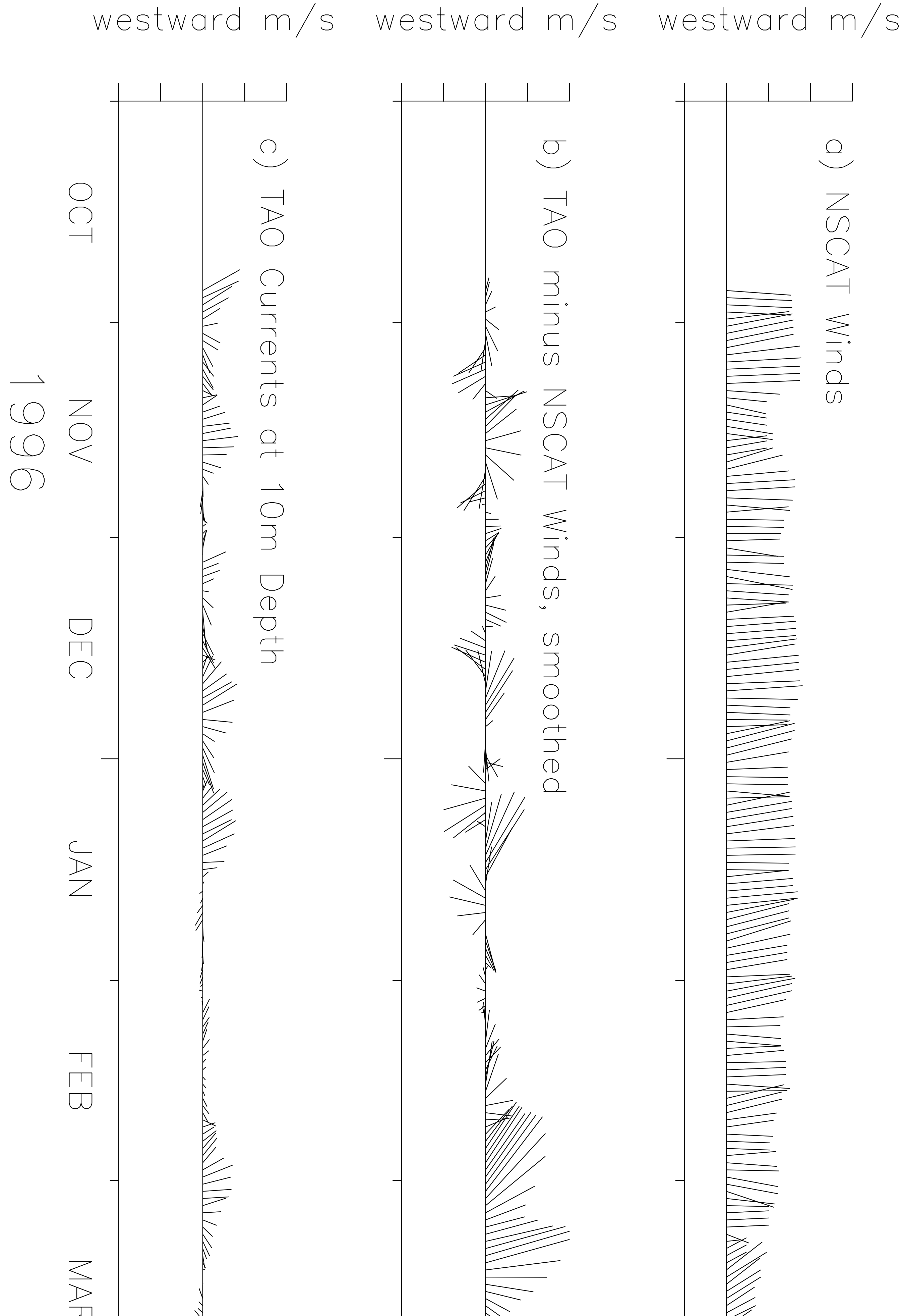
westward m/s
westward m/s
westward m/s
a) NSCAT Winds
b) TAO minus NSCAT Winds, smoothed
c) TAO Currents at 10m Depth
OCT
NOV
DEC
JAN
FEB
1996